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N64 13282

CODE-1

Technical Report No. 32-514

(NASA CR-53027; JPL-TR-32-514)

The Solar-Wind Velocity and its Correlation with Cosmic-Ray Variations and with Solar and Geomagnetic Activity

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MICROFILM $ 0.80 mf.

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OTS

doublecode 5545009

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

October 15, 1963

19p ref

(NASA Contract NAS7-100; Contract AT(30-1)-2098)

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PREFACE

U. R. Rao is on leave of absence from the Physical Research Laboratory, Ahmedabad, India. At the time this report was written he was with the Massachusetts Institute of Technology, Cambridge, Massachusetts. His present address is Southwest Center for Advanced Studies, P.O. Box 8478, Dallas 5, Texas.

ABSTRACT

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Mariner II obtained data on the interplanetary plasma during the period August 29, 1962, through January 3, 1963. The daily average of plasma velocity is presented and compared with data on cosmic-ray diurnal variations and with indices of solar and geomagnetic activity for this period. The only close correlation found is that between plasma velocity and the geomagnetic index K_p. The plasma velocity showed a very strong 27-day recurrence tendency and a close association with M-region geomagnetic storms, which indicates that solar M-regions are emitters of high-velocity plasma. No dependence of plasma velocity on solar distance between 1.0 and 0.7 AU could be detected. AUTHOR

I. INTRODUCTION

Until recently the properties of interplanetary plasma had been derived indirectly – mainly from the analysis and interpretation of Earth-based observations on the scattering of visible sunlight, acceleration of comet tails, variations in radio wave sources observed through the solar corona, and correlation of solar activity with cosmic-ray and geomagnetic phenomena. For a summary of these investigations, see Ref. 1. The first successful attempt to observe interplanetary plasma directly was made with ion traps on the Lunik space probes; a flux of positive ions of about 2×10^8 particles cm^{-2} sec^{-1} was found beyond a distance of 39 Earth radii (Ref. 2 and 3). These observations did not provide information on the energy spectrum of the plasma. With a plasma probe aboard Explorer X, the ion flux was measured as a function of particle energy (Ref. 4 and 5), but because the samples were taken very close to the Earth and for a relatively short period of time, the results may not accurately represent the true properties of interplanetary plasma.

The strongest direct evidence for the existence of a continuous flux of solar plasma (wind) was obtained by the positive-ion spectrometer on Mariner II. Some preliminary results from this experiment have been published elsewhere (Ref. 6 and 7). This report presents the results of a preliminary but more detailed study of the direct measurement of plasma velocity by Mariner II and of the correlation of this velocity with various indices of solar and terrestrial activity during more than 4.5 solar rotations. The results appear to elucidate the physical significance of the planetary index K_p and the nature of M-region geomagnetic storms.

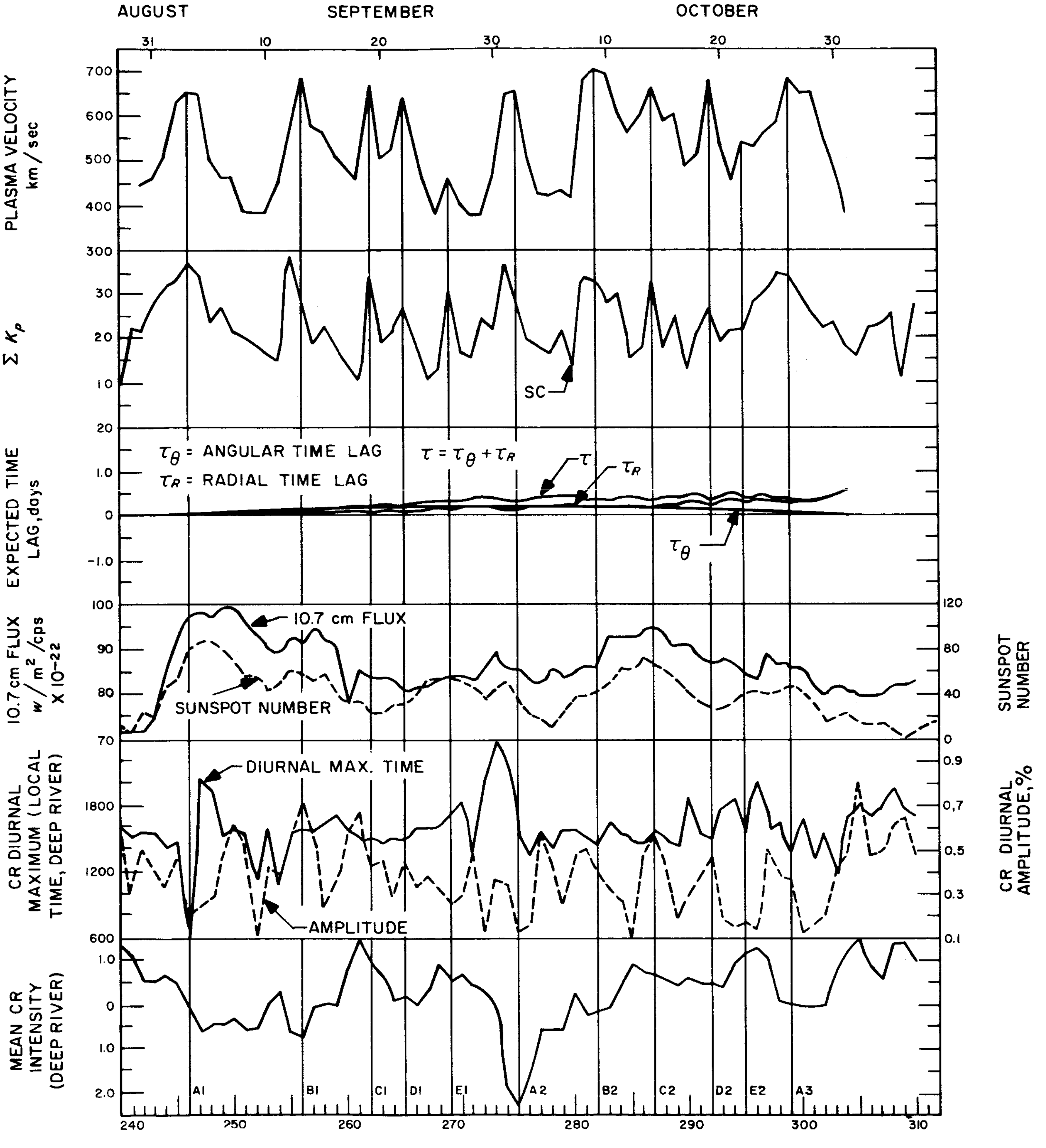

Fig. 1. Plots from August 28, 1962, (240) to November 6, 1962, (310) of (a) daily mean plasma velocity, (b) ΣK_p, (c) *expected* time delay between plasma features observed at the spacecraft and on the Earth, (d) Zurich sunspot number and 10.7 cm flux, (e) cosmic-ray diurnal amplitude and time of diurnal cosmic-ray maximum at Deep River, (f) daily mean cosmic-ray intensity measured at Deep River

cancel each other, so that time lags greater than about one day would not be expected between the spacecraft and the Earth.

A. Plasma Velocity and Cosmic-Ray Variations

It has been postulated that most of the variations observed in cosmic-ray intensity at the Earth are the result of the modulation of galactic cosmic-ray intensity by streams of solar plasma carrying magnetic fields. Assuming the equatorial solar magnetic field to be twisted into an Archimedes spiral which co-rotates with the Sun, Ahluwalia and Dessler (Ref. 10) have shown that induction effects cause motion of the guiding center of the particles in this field, which produces a diurnal variation of cosmic-ray intensity together with a shift of the time-of-maximum to later hours. This model should apply when the solar-wind velocity is free of turbulence, and the geomagnetic field is relatively undisturbed. Even though the time averaged diurnal variation observed on the Earth for the period July 1957 through December 1958 agreed with the model, in that the variation was consistent with a rigidity-independent anisotropy (Ref. 11), it has not been possible to test the theory rigorously.

It can be seen from Fig. 1 and 2 that there was no obvious correlation of the cosmic-ray diurnal amplitude or the time-of-maximum with the plasma velocity. Furthermore, no relationship was observed even when only geomagnetically quiet days were considered. It is particularly interesting to note that in the later part of the observation period, when the plasma velocity underwent large variations from day to day, the time of the cosmic-ray diurnal maximum remained steady at approximately 1600 universal time. Thus, the Mariner plasma observations give no support to the details of Ahluwalia's and Dessler's theory. We do not wish to imply that the basic model of co-rotation of the solar magnetic field is in error but, rather, that the theory is probably oversimplified and does not include all the processes responsible for the daily variation of cosmic-ray intensity.

There did appear to be a tendency for the cosmic-ray daily mean intensity to be negatively correlated with plasma velocity; the correlation, however, was not very good.

B. Plasma Velocity and Solar Activity Indices

It can be observed from Fig. 1 and 2 that no strong correlation existed between sunspot number or 10.7 cm flux and plasma velocity, indicating a lack of relationship between the *overall* solar activity and plasma velocity. There were, however, apparent associations of plasma-velocity maxima with specific solar features, such as radio emission or calcium plage regions. These associations will be discussed further in a future paper.

C. Plasma Velocity and K_p Index

From the fluctuations seen in many individual observatory magnetograms, a planetary index, K_p, is derived which has been traditionally taken to be a measure of the intensity of the solar particle radiation (Ref. 12). According to this picture, low K_p indicates very little plasma flowing past the magnetosphere and high K_p signifies an intense solar-wind flux. Recently, Dessler and Fejer (Ref. 13 and 14) have proposed an alternate explanation according to which K_p is an index of the time rate of change of pressure (plasma plus magnetic) on the magnetosphere. Following this model, one would expect to get only low K_p when a high-velocity solar wind blows steadily for a few days. Similarly, on the assumption that a turbulence is created when a high-velocity plasma overtakes a low-velocity plasma (for example, Ref. 15), the increase in K_p is expected to occur before the plasma velocity reaches its maximum.

In Fig. 1 and 2 there is a remarkable correlation between ΣK_p and plasma velocity with no time lag or phase shift, except perhaps after day 352, when both the *expected* and the observed time lags were approximately one day. (The days are numbered consecutively from the 1st day, January 1, through the 365th day, December 31.) For easy comparison, peaks in plasma velocity are indicated in Fig. 1 and 2 by vertical lines. It can be seen that every major peak and trough in the plasma velocity was associated with a corresponding peak or trough in ΣK_p. The correlation coefficients between plasma velocity and ΣK_p for 15-day periods and for the entire period have been calculated. The correlation coefficient was very high throughout, being 0.73 ± 0.04 for the entire period. (Zero time lag was assumed for this calculation.)

In Fig. 3 the graphs of plasma velocity and K_p, averaged over intervals of six hours for two selected periods of high velocity, are shown. (Note: The relative lack of structure in velocity has been artificially created by the scheme used to approximate the velocity.) It is clear from the figure that even when the solar plasma velocity was continuously high for a few days, K_p did not become small. The correlation between plasma velocity and K_p

was remarkably high even when values averaged over intervals shorter than one day were considered; for example, the correlation between 6-hourly K_p and average plasma velocity had a coefficient of 0.65 ± 0.04.

There is no evidence in Fig. 3 of any increased variability in plasma velocity during periods when the velocity was high. A detailed study of selected 6-hour intervals showed that the variations of plasma flux and velocity from one spectral measurement cycle to the next may have been slightly greater at the higher velocities; this effect, if actually present, was not large but will be investigated further.

Thus, the data show that within the time-resolution capability of the Mariner instrument (3.7 minutes), K_p is a measure of plasma velocity and probably not a measure of the time rate of change of plasma velocity. This experiment did not rule out the possibility that high-frequency ($> \sim 0.005$ cps) turbulence might be a source of geomagnetic disturbances.

The number density and temperature of the protons in the plasma can be calculated from the measured plasma spectra if some simple model is assumed (e.g., isotropic temperature and a Maxwell-Boltzmann velocity distribution superimposed on the bulk motion). Such an analysis has not been completed, but preliminary studies of a limited number of spectra indicate that neither the density n, the flux nv, the kinetic pressure nmv^2, nor the temperature of the plasma had as good a correlation with K_p as did the velocity v. The time variations of these calculated functions are being studied further.

D. Some Interesting Extrapolations

Another way to illustrate the relationship between ΣK_p and the daily mean plasma velocity is by the scatter diagram of Fig. 4. If the relationship is assumed to be a linear one, then a least-squares fit to the data gives the line shown in the figure, which has the equation

$$v(\text{km/sec}) = (8.44 \pm 0.74)\, \Sigma K_p + (330 \pm 17)$$

If we assume this relation is correct, we can use it to determine the plasma velocity at any time in the past three decades from the published values of K_p. It is apparent from inspection that the scatter of the data is such that ΣK_p might equally well be related to v^n, where

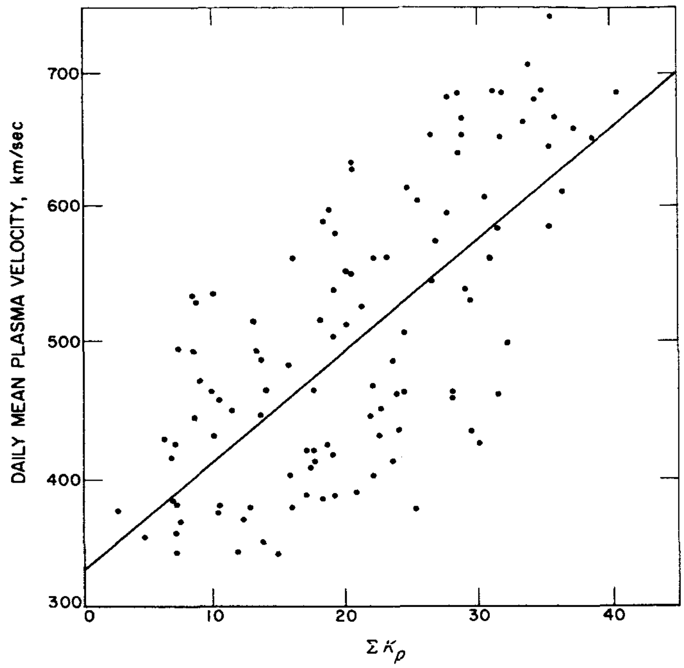

Fig. 4. Scatter diagram of daily mean plasma velocity vs ΣK_p. The line is the least-squares, linear fit to the points

the exponent n differs considerably from unity in either direction. Thus, the evaluation of past plasma velocities cannot be relied upon to be much more than suggestive.

The extrapolated velocity corresponding to $K_p = 0$ is 330 km/sec, which may represent the minimum plasma velocity that can excite disturbances in the geomagnetic field. During the entire mission, the geomagnetic field was quiet for a protracted period only once, for 18 hr on November 17 and 18 when K_p remained zero. The plasma velocity at this time varied approximately between 315 and 360 km/sec.

Extrapolating the function in the opposite direction, a 3-hour K_p of 9 during an intense magnetic storm would correspond to a plasma velocity of 938 km/sec. The year of maximum K_p, during the past solar cycle, extended from September 1957 through August 1958; for that year the calculated average velocity is 530 km/sec, which can be compared with an average velocity of 504 km/sec for the four months of the Mariner II experiment.

It is expected that in the encounter of the magnetosphere by the *supersonic* flow of the solar wind a shock front is formed ahead of the cavity, as has been previously pointed out (Ref. 5, 16, 17). From simple physical their high velocity. Each of the nineteen peaks marked with vertical lines in Fig. 1 and 2 has another peak approximately 27 days earlier or later. The peaks can be divided fairly unequivocally into five groups, designated by the letters A to E, where each member of a group represents an encounter with the same long-lived plasma stream. The numeral following the letter in Fig. 1 and 2 indicates the order of appearance of a particular peak in the group. It is significant that only two of the 19 geomagnetic disturbances produced by these streams were considered to have sudden commencements (marked SC in Fig. 1 and 2) by a large number of observers (Ref. 21).

The persistence of the streams of high-velocity plasma is portrayed in Fig. 5. The 8-day gap in the data in the middle of solar rotation number 1769 makes it uncertain whether the B-peaks and the F-peaks constituted one group or two, but it is believed that they had different sources. The evidence linking peak C4 in rotation number 1770 with the other three C-peaks is not very convincing, but there is little doubt about the others. Particularly notable is the A-stream, which reached its peak between the 7th and 10th days of the rotation. It appears to be associated with a region of the photosphere, which, time after time, contained from one to three calcium plages, which divided and coalesced in a rather complex pattern. Beginning in rotation number 1766 with McMath plage number 6504, this active region was still visible in rotation 1777. During the same period, the corresponding recurring geomagnetic disturbance showed up clearly in the daily character figures. (See, for example, the Göttingen chart in the June 1963 issue of the Compilations of Solar-Geophysical Data by the Central Radio Propagation Laboratory.)

The exact location of the hypothetical M-regions which emit high-velocity plasma and the nature of their association, if any, with active regions, has been the subject of considerable controversy. The most recent statements of the opposing views were those of Saemundsson (Ref. 22) and Mustel (Ref. 23), who respectively deny and affirm that the streams emerge from active regions. It was hoped that, with the velocity of the stream having been measured, it would be straightforward to determine from the transit time precisely the point of origin on the Sun. The first attempt to do this in a simple way, however, did not clarify the situation. Therefore, this problem has been deferred to a subsequent paper, where it will be discussed in detail with more accurate velocity determinations.

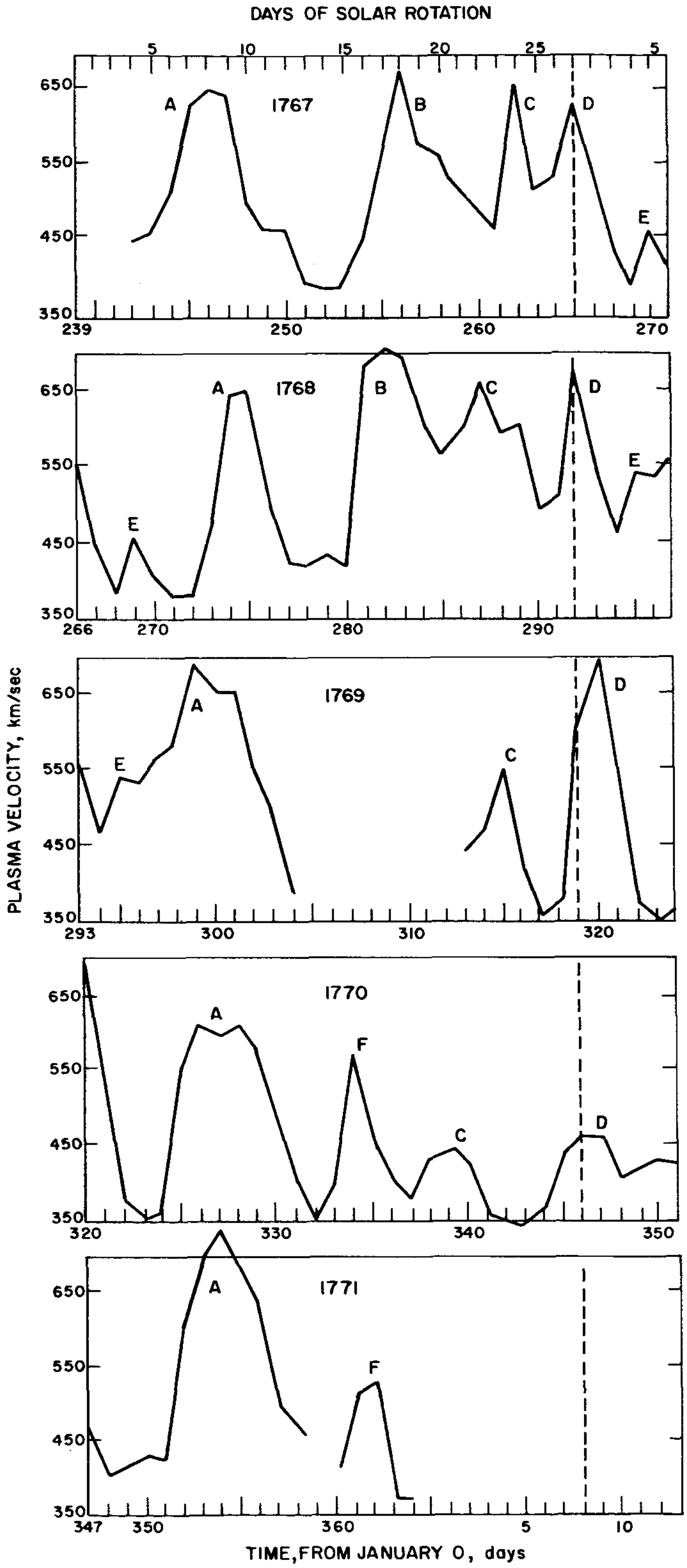

Fig. 5. Daily mean plasma velocity vs time, aligned to show the approximate 27-day recurrence

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ACKNOWLEDGMENT

The complex electronics necessary for the successful performance of this experiment was developed by C. S. Josias, J. L. Lawrence, Jr., and H. R. Mertz, of the Jet Propulsion Laboratory (JPL) California Institute of Technology. We are happy to acknowledge our great indebtedness to them.

This report presents the results of research carried out at JPL and the Massachusetts Institute of Technology (MIT). The research performed at JPL was done under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration. The work at MIT was supported by funds provided by the U. S. Atomic Energy Commission, under Contract AT-(30-1)-2098.